Experimental study of fire tornado

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Results of fire tornado investigations under model conditions are presented. The tornado has been formed via rotating a tank filled with a burning substance (spirit) by an electric motor. The conditions for the stable tornado formation at different revolutions of the tank both at free spirit burning and at altitudinal limitation of the flame have been determined.

Introduction

Last years, the coherent structures, including, particularly, various tornados and swirling flows, are of increasing interest.[1–8] The results of theoretical and experimental investigations of physical characteristics of whirlwinds and tornados, the conditions for their formation and stability were considered. The medium in such flows is complicated and random, where spatiotemporal fields of temperature, speed, and refraction index continuously fluctuate.

Conditionally, in view of the magnitude of the refraction index fluctuation, coherent structures can be divided into two groups: structures with temperature close to the ambient temperature and structures with temperatures significantly exceeding the ambient one, mainly, flames of fuel combusting in different conditions and fire tornados.

Fire tornados refer to atmospheric tornados, which are ecological natural catastrophes followed by heavy damages. According to observations, natural fire tornados occur at forest fires and mass fires in building areas, at lumber factories. A fire tornado is accompanied by noticable radial air in-flow from all directions to the base of the central convective column with simultaneous swirling of the flow.

Powerful natural tornados originate from rotating mother clouds and go down to the ground like trunks. The rotation speed at the periphery can attain the sound speed. The rotation is the feature discriminating tornado clouds from others. A large centrifugal force, resulting from the effect of the principle of conservation of moment of momentum, is compensated with the external pressure and a low pressure inside the tornado. The air flow in the tornado's trunk is formed with fine vortex filaments, a quantity of which interacts with each other and rotates like an elastic solid (rubber cord).

Experimental studies of conditions favorable for formation of various types of vortex-type flows, including tornado-like vortexes formed over a heated disk rotating in the atmosphere of an immovable air, are described in Ref. 1. The flow was visualized by means of evaporation of colophony from the disk surface. As it has been shown,[1] a tornado-like vortex originates when the speed of disk rotation is $\approx (2.3 \pm 1.5)$ rev.$\cdot$s^{-1} while an ordinary swirling turbulent flow is observed at less or larger speeds of rotation. Such type of tornados, in contrast to fire ones, can be conventionally called “heat”.

The fire tornado is a more complicated physical phenomenon. It is meant that the convective coloumn at mass fires and high-intensity fires, attaining altitudes of several kilometers, forms a thundercloud. This artificial cloud can rotate in some cases and, in its turn, form a fire tornado. A fire tornado has some additional features discriminating it from ordinary atmospheric tornados:

1) the presence of a source of energy (2000–13000 kkal/kg depending on the combustible material) in sufficiently large amount due to the combustion of burning gases, which are evolved as the result of pyrolysis (solid) or evaporation (liquid) of combustible materials. The convective column of heated gases originates over the burning material due to the effect of the Archimedean force;

2) powerful inflow of an oxidant, required for combustion of combustible materials (4–17 m^3/kg of air) to the burning area, where intense oxidation reactions take place.

The conditions for forming and keeping a tornado in a steady state are determined by the balance of forces affecting the medium in the rotating convective column, i.e., the centrifugal force, the environmental pressure force, the Archimedean lifting force, forces induced by the pressure distribution (decreased at the tornado axis) inside a tornado; the external force due to the influence of the wind speed.

A simulation model for forecasting the dynamic of fire formations at free air has been worked out[7] on the base of generalized set of equations of unsteady two-dimensional turbulent flow of viscous compressible gas with the account for combustion. Characteristic features of fire tornados have been determined; it was shown that tornados have the shape of vertical cylindrical column 2-3 times higher than in the case of the diffused burning, the temperature is virtually invariable with the height,

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the pressure at the axis is less than in the environment.

The results of study of fluctuations of the parameters of a laser beam propagating through a convective column and swirling fire flow, which is a fire tornado model, are considered in Refs. 10 and 11. The structure and physical parameters of the medium must be known to interpret the results. The results of studying parameters of a fire tornado simulated under laboratory conditions are considered in this work.

Measurement instrumentation

The scheme of the stand is shown in Fig. 1. A fire tornado was simulated by rotating a cylindrical tank of 100 mm in diameter and 20 mm in side height filled with a burning substance (20, 30 ml of spirit). The tank was mounted on a disk of 400 mm in diameter rotated with a DC motor.

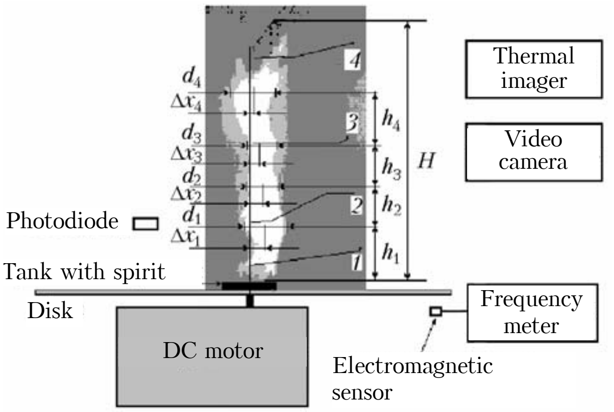


Fig. 1. The scheme of the measuring stand. Measured tornado parameters.

Motor speed was controlled by varying the feeding voltage, the speed of rotation was measured with the frequency meter from pulses of the electromagnetic sensor. To exclude the influence of air vibrations on the tornado structure, the device was placed into a chamber (with a base of 0.6×0.6 m and a height of 1.7 m) with closed sidewalls; front side of the chamber was closed with a Dacron film (transparent in the visible and IR regions) through which the burning process was recorded with the thermal imager and video camera.

The measurements were carried out in two modes: with open top of the chamber and with a barrier (steel plate) placed at heights z of = 0.4 or 0.5 m above the tank. In the second case, a barrier was simulated, stabilizing a swirling flow. A TV camera Sony was used to record the burning process in the visible range and the automated thermal imaging system AGA-780 – in the 3–5 μm range. The photodiode fixed at a height of 100 mm was used to record fluctuations of the light flux from the burning substance in the visible range.

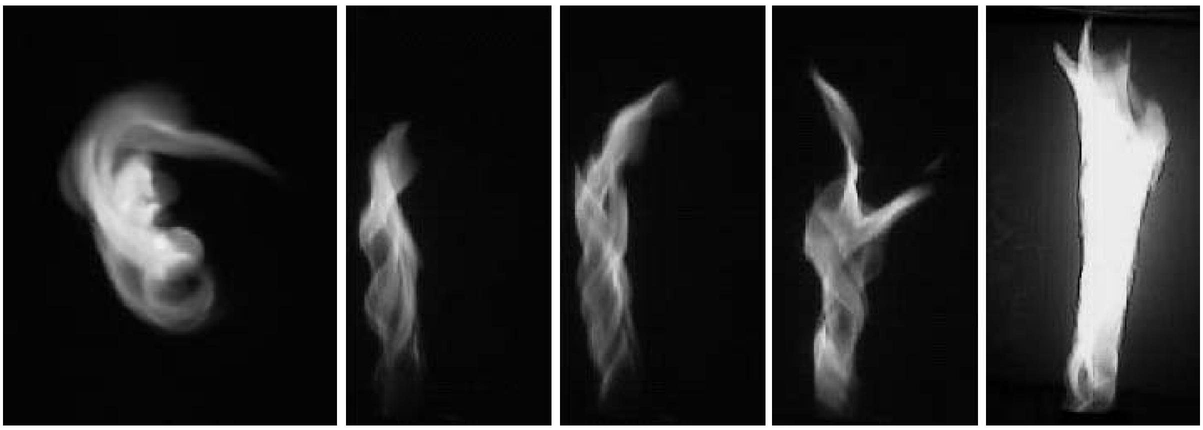
The temperature was measured using fixed thermocouples (*1–4* in Fig. 1), movable thermocouple, and with the thermal imaging technique.[9] Thermocouples of about 0.25 mm in diameter were fixed at heights of 30, 50, 100, and 200 mm above the surface of the tank with the burning substance. The ambient temperature was invariable and equal to 17–19 °C. The data from the thermocouples, TV camera, and photodiode went into the computer for the processing.

Measurement results

Measurements in the visible range

The following tornado parameters were visually determined by TV cam images with the use of Photoshop at the level of visual brightness (see Fig. 1): the height H, the coil height h_i (in coils, characteristic for the tornado structure), diameters d_i, and the displacement Δx_i (i is the number of section) of the tornado axis from the rotation axis.

Images illustrating the shape of tornado at different instants are shown in Fig. 2. Note, that the tornado shape varies very quickly (images in Figs. 2 *b* and *c* were obtained at an interval of 0.04 s under short exposures). Helical cords forming the tornado are well seen. The first tornado coil h_1 has the maximal height.



a *b* *c* *d* *e*

Fig. 2. Tornado shape: view from above (*a*) and side views (*b–d*) in the case of open chamber and side view with the chamber covered at a height of 0.5 m (*e*).

Bursts from the tornado body top are observed (Fig. 2d). In some points of time, fire partition to 2–3 parts is observed. On average, the top of the fire is close to cone. The fire has a bluish tint near the burning surface in contrast to another part of the tornado, the color of which is displaced to the long-wave region.

A barrier over the tornado results in its stabilization. The tornado becomes stable during the whole time of the burning, precession is absent, the tornado diameter increases.

The measurable tornado parameters fluctuate in time. This is obvious from Fig. 3 exemplifying the parameters at stable burning in the tornado mode. The time of steady burning in such mode is 8–15 s, then the tornado falls and is reduced again.

Table 1 presents the burning-time average tornado parameters for two simulation modes: with the open and covered top chamber (the chamber was covered with a steel plate at the height z). The essential dependence of the tornado parameters on the simulation mode is evident from the table.

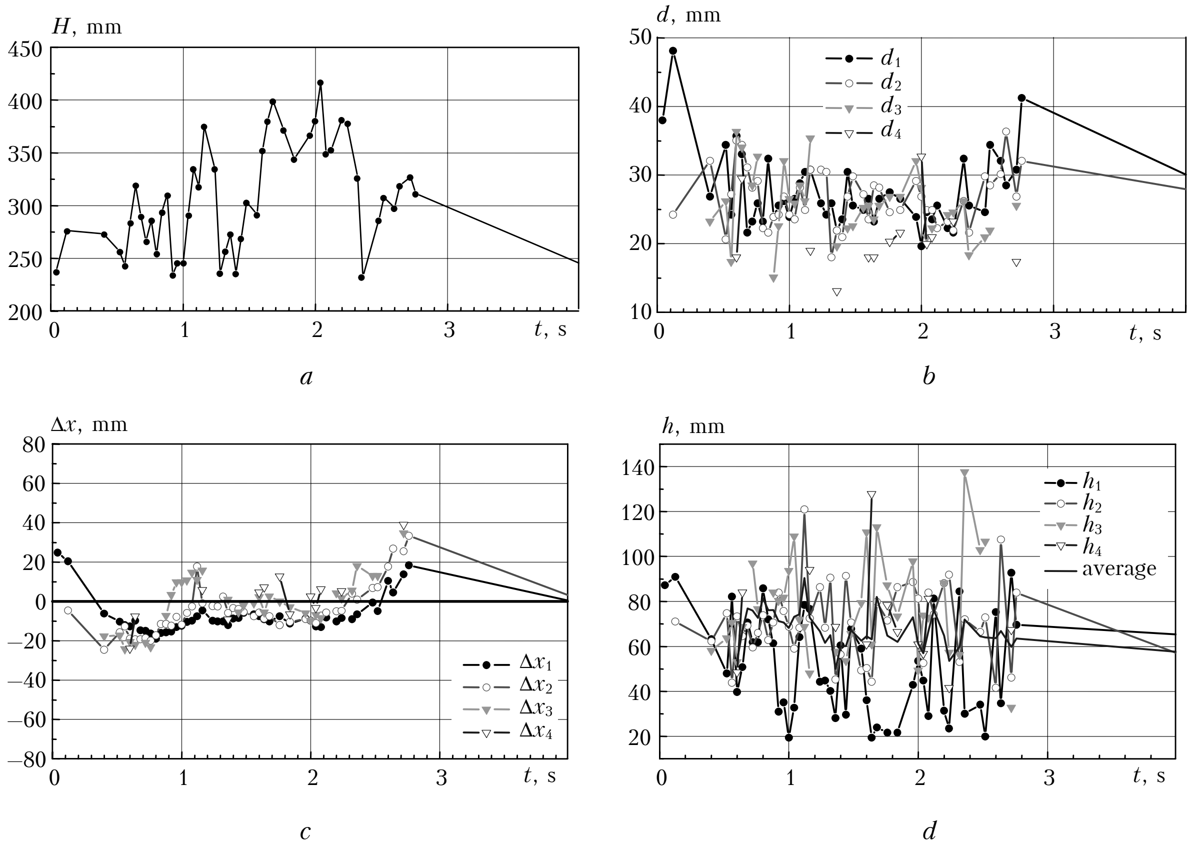


Fig. 3. Temporal variations of tornado parameters: the height (a), diameter (b), axis misalignment (c), and height of coils (d).

Table 1. Average geometrical sizes of the tornado under different simulation conditions

Parameter, mm	Without limitation		Height limitation z, m			
			0.5		0.4	
	AV	RMS	AV	RMS	AV	RMS
d_0	30	10	59	10	60	12
d_1	28	7	60	13	55	12
d_2	26	5	66	17	53	11
d_3	22	5	104	20	109	26
Δx_1	−9	15	–	–	–	–
Δx_2	−4.6	17	–	–	–	–
Δx_3	−5	13	–	–	–	–
Δx_4	6	15	–	–	–	–
H	290	55	430	30	380	20
h_1	54	20	98	9	70	9
h_2	74	17	96	11	90	10
h_3	75	20	155	30	150	20

N o t e . AV are average values and RMS are root mean square deviations.

Table 2. The comparison of tornado parameters for two simulation modes

Open chamber top	Closed chamber top
1. Relatively stable tornado is formed at a disk rotation speed of ~(3.8 ± (0.2–0.4)) rev./s. Revolution changes result in tornado fall and transfer to the rotating turbulent burning. The tornado axis precession is observed, i.e., displacement from the rotation axis of the tank with burning substance and quite low rotation of the tornado axis at a speed of 0.1–0.15 rev./s. over the tank surface with the displacement from the center to a distance larger than the tornado radius	1. Stable tornado is also formed at a disk rotation speed of ~3.8 rev./s and keeps when increasing rotation speed to maximally measured values of about 8 rev./s. The acceleration results in some increase of the tornado diameter. Tornado axis precession is virtually unobservable
2. The shape of tornado quickly varies in time and is close in average to a cylinder with a diameter of 30–40 mm slowly decreasing to the end of burning to 20 mm	2. The shape of tornado is stable up to full burn-out and close to a cylinder of about 60 mm in diameter with an expanding cone or separate tips near a barrier, spreading along the barrier surface
3. An average tornado height is about 290 mm, i.e., significantly less then in the case of the barrier presence, and approaches 400 mm only in some measurements	3. The tornado height is about 430 mm at $z = 0.5$ m and about 380 mm at $z = 0.4$ m close to the barrier height
4. The height of coils quickly varies in time within about 50–75 mm	4. The height of coils is stably about 60–150 mm
5. The ratio of the circumference over coil diameter to its height defines the ratio of the tangential speed V_t to the vertical one V_v ($2\pi d_i/h_i = V_t/V_v$) and is about 1.6 for the first coil and about 1 for the second and third ones	5. The ratio $2\pi d_i/h_i = V_t/V_v$ ~2 for all coils

The results of analysis of the tornado parameters for the two modes are cited in Table 2.

Measurements of tornado parameters in the IR region

The example of tornado image (100 × 100 pixels) obtained with the thermal imaging system is shown in Fig. 4.

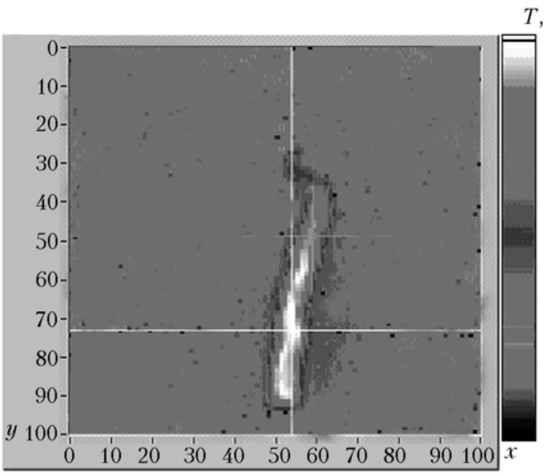


Fig. 4. The example of the thermal image of tornado.

When frame-processing, the maximal temperature and its coordinates, the tornado height and its diameter were determined. The height and cross section distributions of temperature were calculated in the time-averaged image. The processing results are given in Figs. 5 and 6.

The analysis of the thermal-imaging measurements has shown the following:

1. Maximal temperature in tornado is 800–950 K, being close to the thermocouples-measured results. The agreement between temperatures measured with a temperature sensor and optically allows the conclusion that the fire radiation is close to 0.9–1 within the 3–5 μm range.

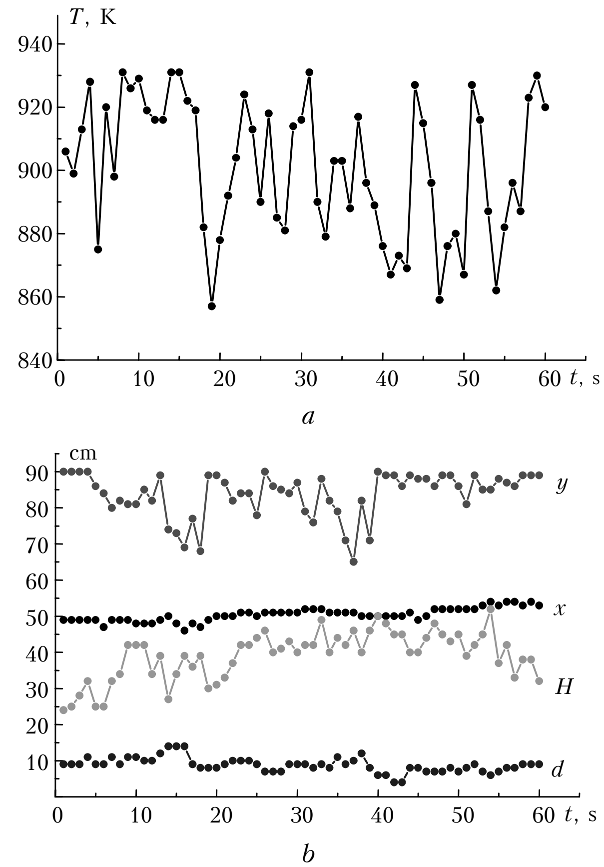


Fig. 5. Time variations of the tornado parameters: maximal temperature (*a*); diameter *d*, height *H*, *y* and *x*-coordinates of the maximal temperature (*b*).

2. Brightness temperature is virtually invariable up to ~2/3 of the tornado height and then quickly falls. The temperature is less than the maximal one near the burning substance surface; this agrees with the data of Ref. 7.

3. Average brightness temperature in the cross section is close to Gaussian.

4. The average tornado diameter is about 100 mm, its height is about 400 mm and somewhat higher than in the visible range due to the fact that only the high-temperature part of fire emits in the visible range. Thermal-imaging measurable temperature range is wider in the IR range.

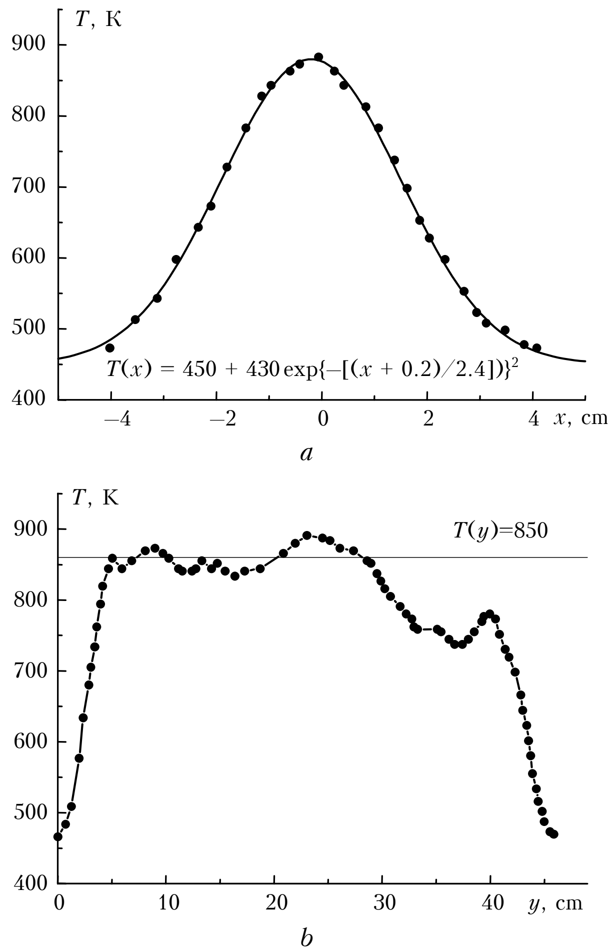


Fig. 6. Thermal imaging measurements of the average temperature: cross section (*a*) and in vertical (*y*-axis) (*b*).

Conclusions

1. When the chamber top is open:

– stable tornado is formed at a limited speed of rotation (~3.8 rev./s) determined by the balance of forces affecting the fire. The tornado has a complicated spiral structure (coils) quickly varying in time; gas moving has tangential and vertical speed components;

– the period of steady burning in the tornado mode is 8–15 s. Note, that the tornado precession (volume-wise axis displacement and slow rotation of ~0.1–0.15 rev./s) is observed with the displacement of its axis from the center to a distance greater than the tornado radius;

– temporal variations of the tornado height are 250–450 mm, of the diameter 20–40 mm, axis displacement ±30 mm, and the coil height 30–140 mm;

– maximal temperatures, measured both with thermocouples and thermal methods, are ~800–1000 K. The brightness temperature is virtually invariable up to ~2/3 of the tornado height and then quickly falls.

2. When the chamber top is closed:

– tornado is formed at a rotation speed of 3.8 rev./s and keeps stable during the whole period of the fuel burning at accelerating to 8 rev./s measured in the experiment; the precession is insignificant;

– the tornado diameter increases with acceleration. It takes the pear shape slightly contracted at a height of ~2/3*h* and significantly expanded near the surface limiting the chamber volume from the top; the tornado height is close to the height of free space between the tank with fuel and the top surface.

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